JC07 Rec'd PCT/PTO 18 MAR 2002

FORM PTO-1390 (Modified) (REV 11-2000) U.S. DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE

TRANSMITTAL LETTER TO THE UNITED STATES DESIGNATED/ELECTED OFFICE (DO/EO/US) CONCERNING A FILING UNDER 35 U.S.C. 371

ATTORNEY'S DOCKET NUMBER
9267-17

U.S. APPLICATION NO (IF KNOWN, SEE 37 CFR
10/088397

INTERNATIONAL APPLICATION NO.	INTERNATIONAL FILING DATE	PRIORITY DATE CLAIMED
PCT/GB00/03496	**September 12, 2000**	**September 17, 1999**

TITLE OF INVENTION
Laser Apparatus For Use In Material Processing

APPLICANT(S) FOR DO/EO/US
Zsolt John Laczik and Frances Nicholas Goodhall

Applicant herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information:

1. ☒ This is a **FIRST** submission of items concerning a filing under 35 U.S.C. 371.
2. ☐ This is a **SECOND** or **SUBSEQUENT** submission of items concerning a filing under 35 U.S.C. 371.
3. ☒ This is an express request to begin national examination procedures (35 U.S.C. 371(f)). The submission must include itens (5), (6), (9) and (24) indicated below.
4. ☒ The US has been elected by the expiration of 19 months from the priority date (Article 31).
5. ☒ A copy of the International Application as filed (35 U.S.C. 371 (c) (2))
   a. ☐ is attached hereto (required only if not communicated by the International Bureau).
   b. ☒ has been communicated by the International Bureau.
   c. ☐ is not required, as the application was filed in the United States Receiving Office (RO/US).
6. ☐ An English language translation of the International Application as filed (35 U.S.C. 371(c)(2)).
   a. ☐ is attached hereto.
   b. ☐ has been previously submitted under 35 U.S.C. 154(d)(4).
7. ☒ Amendments to the claims of the International Application under PCT Article 19 (35 U.S.C. 371 (c)(3))
   a. ☐ are attached hereto (required only if not communicated by the International Bureau).
   b. ☐ have been communicated by the International Bureau.
   c. ☐ have not been made; however, the time limit for making such amendments has NOT expired.
   d. ☒ have not been made and will not be made.
8. ☐ An English language translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371(c)(3)).
9. ☐ An oath or declaration of the inventor(s) (35 U.S.C. 371 (c)(4)).
10. ☐ An English language translation of the annexes to the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. 371 (c)(5)).
11. ☒ A copy of the International Preliminary Examination Report (PCT/IPEA/409).
12. ☒ A copy of the International Search Report (PCT/ISA/210).

Items 13 to 20 below concern document(s) or information included:

13. ☒ An Information Disclosure Statement under 37 CFR 1.97 and 1.98.
14. ☐ An assignment document for recording. A separate cover sheet in compliance with 37 CFR 3.28 and 3.31 is included.
15. ☒ A **FIRST** preliminary amendment.
16. ☐ A **SECOND** or **SUBSEQUENT** preliminary amendment.
17. ☐ A substitute specification.
18. ☐ A change of power of attorney and/or address letter.
19. ☐ A computer-readable form of the sequence listing in accordance with PCT Rule 13ter.2 and 35 U.S.C. 1.821 - 1.825.
20. ☐ A second copy of the published international application under 35 U.S.C. 154(d)(4).
21. ☐ A second copy of the English language translation of the international application under 35 U.S.C. 154(d)(4).
22. ☒ Certificate of Mailing by Express Mail
23. ☒ Other items or information:

Courtesy Copy of Publication PCT/GB00/03496
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U.S. Express Mail Label No. 931090779

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U.S. APPLICATION NO. (IF KNOWN, SEE 37 CFR	INTERNATIONAL APPLICATION NO.	ATTORNEY'S DOCKET NUMBER
10/088397	PCT/GB00/03496	9267-17

24. The following fees are submitted:.

BASIC NATIONAL FEE (37 CFR 1.492 (a) (1) - (5)) :

		CALCULATIONS	PTO USE ONLY
☐ Neither international preliminary examination fee (37 CFR 1.482) nor international search fee (37 CFR 1.445(a)(2)) paid to USPTO and International Search Report not prepared by the EPO or JPO	**$1040.00**		
☒ International preliminary examination fee (37 CFR 1.482) not paid to USPTO but International Search Report prepared by the EPO or JPO	**$890.00**		
☐ International preliminary examination fee (37 CFR 1.482) not paid to USPTO but international search fee (37 CFR 1.445(a)(2)) paid to USPTO	**$740.00**		
☐ International preliminary examination fee (37 CFR 1.482) paid to USPTO but all claims did not satisfy provisions of PCT Article 33(1)-(4)	**$710.00**		
☐ International preliminary examination fee (37 CFR 1.482) paid to USPTO and all claims satisfied provisions of PCT Article 33(1)-(4)	**$100.00**		
ENTER APPROPRIATE BASIC FEE AMOUNT =		**$890.00**	
Surcharge of **$130.00** for furnishing the oath or declaration later than ☐ 20 ☒ 30 months from the earliest claimed priority date (37 CFR 1.492 (e)).		**$130.00**	

CLAIMS	NUMBER FILED	NUMBER EXTRA	RATE		
Total claims	16 - 20 =	0	x $18.00	**$0.00**	
Independent claims	3 - 3 =	0	x $84.00	**$0.00**	
Multiple Dependent Claims **(check if applicable)**.			☐	**$0.00**	
TOTAL OF ABOVE CALCULATIONS =				**$1,020.00**	
☒ Applicant claims small entity status. See 37 CFR 1.27). The fees indicated above are reduced by 1/2.				**$510.00**	
SUBTOTAL =				**$510.00**	
Processing fee of **$130.00** for furnishing the English translation later than ☐ 20 ☐ 30 months from the earliest claimed priority date (37 CFR 1.492 (f)). +				**$0.00**	
TOTAL NATIONAL FEE =				**$510.00**	
Fee for recording the enclosed assignment (37 CFR 1.21(h)). The assignment must be accompanied by an appropriate cover sheet (37 CFR 3.28, 3.31) **(check if applicable).** ☐				**$0.00**	
TOTAL FEES ENCLOSED =				**$510.00**	
				Amount to be: refunded	$
				charged	$

a. ☒ A check in the amount of **$510.00** to cover the above fees is enclosed.

b. ☐ Please charge my Deposit Account No. ______ in the amount of ______ to cover the above fees. A duplicate copy of this sheet is enclosed.

c. ☒ The Commissioner is hereby authorized to charge any additional fees which may be required, or credit any overpayment to Deposit Account No. **50-0573** A duplicate copy of this sheet is enclosed.

d. ☐ Fees are to be charged to a credit card. **WARNING:** Information on this form may become public. **Credit card information should not be included on this form.** Provide credit card information and authorization on PTO-2038.

NOTE: Where an appropriate time limit under 37 CFR 1.494 or 1.495 has not been met, a petition to revive (37 CFR 1.137(a) or (b)) must be filed and granted to restore the application to pending status.

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36,469
REGISTRATION NUMBER

March 18, 2002
DATE

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PATENT

Attorney Docket No.: 9267-17

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re:	Patent application of Zsolt John Laczik et al.	:	
Serial No.:	Not Yet Assigned	:	International Application PCT/GB00/03496
Filed:	Herewith	:	International Filing Date: September 12, 2000
For:	Laser Apparatus For Use In Material Processing	:	

PRELIMINARY AMENDMENT

Commissioner for Patents
Box PCT
Washington, D.C. 20231

Sir:

Prior to examination in the United States Patent and Trademark Office, please make the following amendments in the above-identified application in order to place it in condition for examination.

CERTIFICATE OF MAILING
UNDER 37 C.F.R. 1.10

EXPRESS MAIL Mailing Label Number: **EL 931090779 US**
Date of Deposit: **March 18, 2002**

I hereby certify that this correspondence, along with any paper referred to as being attached or enclosed, and/or fee, is being deposited with the United States Postal Service, "EXPRESS MAIL–POST OFFICE TO ADDRESSEE" service under 37 C.F.R. 1.10, on the date indicated above, and addressed to: Commissioner for Patents, Washington, D.C. 20231.

Therese McKinley
Signature of person mailing page.

Therese McKinley
Type or print name of person

PHIP\320123\1

AMENDMENT

Please amend the application as follows, without prejudice.

In the Claims:

Please amend the claims as follows. (A marked up copy of the claims is included in the Appendix to this Preliminary Amendment.)

5. (Amended) The laser conditioning apparatus as claimed in claim 4, wherein the phase filter is a programmable spatial light modulator.

6. (Amended) The laser conditioning apparatus as claimed in claim 4, wherein each region of the filter has a phase shift of either 0 or π radians.

7. (Amended) The laser conditioning apparatus as claimed in claim 4, wherein the phase filter produces a desired three dimensional geometry of the light incident on the workpiece.

8. (Amended) The laser conditioning apparatus as claimed in claim 4, wherein the phase filter produces a plurality of separate intensity peaks.

New Claims:

Please add the following new claims to the application.

13. The laser conditioning apparatus as claimed in claim 1, wherein the phase filter is a programmable spatial light modulator.

14. The laser conditioning apparatus as claimed in claim 1, wherein each region of the filter has a phase shift of either 0 or π radians.

15. The laser conditioning apparatus as claimed in claim 1, wherein the phase filter produces a desired three dimensional geometry of the light incident on the workpiece.

16. The laser conditioning apparatus as claimed in claim 1, wherein the phase filter produces a plurality of separate intensity peaks.

REMARKS

Claims 1-10, 13-16 are pending in the application after entry of the instant amendments and all Article 34 amendments. Claims 5-8 have been modified to remove multiple dependencies. Claims 13-16 have been added and depend from claim 1. No new matter has been introduced.

Applicants look forward to an early action on the merits.

Respectfully Submitted,

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BY

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APPENDIX - MARKED UP COPY OF AMENDED CLAIMS

5. (Amended) The laser conditioning a [A]pparatus as claimed in [any one of the preceding claims] claim 4, wherein the phase filter is a programmable spatial light modulator.

6. (Amended) The laser conditioning a[A]pparatus as claimed in [any one of the preceding claims] claim 4, wherein each region of the filter has a phase shift of either 0 or π radians.

7. (Amended) The laser conditioning a[A]pparatus as claimed in [any one of the preceding claims] claim 4, wherein the phase filter produces a desired three dimensional geometry of the light incident on the workpiece.

8. (Amended) The laser conditioning a[A]pparatus as claimed in [any one of the preceding claims] claim 4, wherein the phase filter produces a plurality of separate intensity peaks.

New Claims:

13. The laser conditioning apparatus as claimed in claim 1, wherein the phase filter is a programmable spatial light modulator.

14. The laser conditioning apparatus as claimed in claim 1, wherein each region of the filter has a phase shift of either 0 or π radians.

15. The laser conditioning apparatus as claimed in claim 1, wherein the phase filter produces a desired three dimensional geometry of the light incident on the workpiece.

16. The laser conditioning apparatus as claimed in claim 1, wherein the phase filter produces a plurality of separate intensity peaks.

LASER APPARATUS FOR USE IN MATERIAL PROCESSING

The present invention relates to laser apparatus for use in material processing and in particular but not exclusively for use in cutting, welding, machining and other related processing techniques of materials.

In conventional laser cutting, welding and machining systems light from a CW or pulsed laser is focused to an approximately diffraction limited spot using refractive lens elements and/or reflective mirrors. When the focused spot is brought into contact with a workpiece the very high light intensity in the focused spot results in localised heating of the workpiece and consequently localised melting, evaporation or ablation of the material occurs. Normally a gas flow co-axial with the optical system is also provided to protect the lens elements by forcing sputtered material away from the lens elements and to enhance the cutting, welding or machining process. In the case of welding the gas is usually inert but for cutting the gas may be corrosive and contribute to the cutting process. The focused spot and the workpiece must be moved with respect to one another in such a way that the workpiece is welded, cut or machined in pre-defined areas.

In many cases, however, the optimum light intensity distribution for the process described above is not the one corresponding to a single diffraction limited focused spot. Instead, it has been found that in some cases the use of two focused spots separated by a few millimetres can be advantageous.

In WO 98/14302 laser cutting apparatus is described in which the light from the laser is imaged to two separated focal points on a common axis by means of a multi-lens or a curved reflective surface. Similarly, in US5521352 laser apparatus for cutting a metal workpiece is described which uses a semi-silvered mirror to split the light from the laser into two beams. The two beams are then directed, using conventional reflective optics, to opposing surfaces of the workpiece.

With the apparatus described in the documents referred to

above the light from a laser beam is focussed to two separated focal spots using conventional refractive/reflective optical elements. In general, the apparatus have very limited degrees of freedom and are inflexible. For example, in WO 98/14302 the only selectable design parameters are the radius of the central region of the lens element and the difference in curvature between the central region and the annulus. This significantly restricts the extent to which characteristics such as the separation between the foci, the power split ratio and the axial and spatial resolution of the foci may be selected and in some cases the opportunity for selection of such characteristics is not available.

Also, once the design parameters are chosen and a lens element with the appropriate radii of the central region and the annulus is provided, the apparatus is only capable of generating the two focal spots as determined by that lens element. To alter the performance characteristics of the apparatus, a completely new alternative lens element would have to replace the existing lens element. Furthermore, it should be noted that the laser cutting apparatus described in the documents referred to above are limited to specific intensity distributions associated with the two separate focus spots.

In GB2278458 a converter for a laser is described that adjusts the intensity profile of the laser beam across a single focused spot. The converter consists of a phase zone plate array consisting of a two dimensional array of close packed diffracting Fresnel zone plates randomly arranged to cause a phase delay of 0 or π radians. The converter is used to reduce fluctuations in intensity across the focal spot and thereby ensures a more uniform focal spot is produced. However, with the converter only the intensity across the focal spot itself is adjusted, the intensity distribution is not altered such that the adjusted distribution extends beyond the focused spot that would be produced without the converter in place. Furthermore, the adjustment of the intensity distribution to increase the uniformity of the intensity is restricted to a plane perpendicular to the optical

axis. The converter cannot alter the intensity distribution of the laser beam in any other way. In particular, the overall distribution of light intensity, the 'envelope' of the light intensity and/or the number of focal spots cannot be altered using the converter described in GB 2278458.

On the other hand, the present invention seeks to provide a novel optical arrangement that is capable of generating arbitrary predetermined three dimensional light intensity distributions that may be optimised for particular laser processing tasks.

The present invention provides laser apparatus for use in material processing of a workpiece, the apparatus comprising a coherent light source, a housing containing one or more focusing elements and a phase filter, the phase filter having a plurality of regions with each region being assigned a predetermined phase shift from a plurality of possible phase shifts, the phase shifts of the plurality of regions being chosen in dependence on a desired intensity distribution of light incident on the workpiece which extends in at least a spatial dimension parallel to the optical axis beyond the focused spot produced by the apparatus in the absence of the filter..

In a preferred embodiment the phase filter is mounted between the one or more focussing elements and the workpiece. The phase filter may be provided in a removable cartridge that is removably mounted within the housing.

In an alternative aspect the present invention provides laser conditioning apparatus for use in material processing of a workpiece, the conditioning apparatus comprising an adapter housing containing a phase filter, the adapter housing having connection means for mounting the adapter housing between a coherent light source and one or more focusing elements, the phase filter having a plurality of regions with each region being assigned a predetermined phase shift from a plurality of possible phase shifts, the phase shifts of the plurality of regions being chosen in dependence on the desired intensity distribution of light incident on the workpiece which extends in at least a spatial dimension parallel to the

optical axis beyond the focused spot produced by a laser apparatus in the absence of the filter.

Ideally, the plurality of phase shift regions of the filter produces an intensity distribution that extends beyond a diffraction limited focused spot in at least one spatial dimension. The phase filter may be arranged to produce a desired three dimensional geometry of the intensity distribution. Alternatively or in addition, the phase filter may produce a plurality of separate intensity peaks.

The phase shifts of the plurality of regions of the filter are iteratively optimised with respect to the desired intensity distribution of the light incident on the workpiece and preferably the phase shifts of the plurality of regions of the filter are iteratively optimised using a direct binary search.

In another aspect the present invention provides a method of manufacturing a phase filter for use in laser material processing apparatus, the method comprising the steps of: determining a desired intensity distribution of light incident on a workpiece which extends in at least one spatial dimension beyond the focused spot produced by the laser material processing apparatus in the absence of the filter; assigning initial respective phase shifts to a plurality of regions of the filter; determining an error factor with respect to the similarity of the intensity distribution generated using the assigned phase shifts to the desired intensity distribution; iteratively optimising the phase shifts assigned to each region so as to determine final phase shifts for each region of the filter; and generating a phase filter with a plurality of regions, each region having the final phase shift determined by the iterative optimisation step.

With the present invention there are very large degrees of freedom in the design of the phase-only filters and this makes it possible to achieve almost any desired intensity distribution defined in a three-dimensional volume around the lens focus. This, in turn, enables high precision, high speed and efficient material processing using a laser. Furthermore, the laser apparatus can be easily adjusted to produce an

alternative intensity distribution simply by altering or replacing the phase-only filter, the main and more expensive part of the apparatus, the focusing lens, can be retained and reused. Where a spatial light modulator is used as the phase-only filter, alteration of the intensity distribution is simply a matter of re-programming the modulator and so the laser apparatus is very flexible and responsive to the individual intensity distribution requirements of particular processing tasks.

It will, of course, be understood that although reference is made herein to laser sources this is intended to generally cover both coherent and partially coherent laser sources.

An embodiment of the present invention will now be described by way of example with reference to the accompanying drawings, in which:

Figures 1a, 1b and 1c are schematic diagrams of a laser focusing system in accordance with the present invention with the phase-only filter in different positions;

Figure 2 is a schematic diagram of a conventional laser focusing system with an adapter incorporating a phase-only filter in accordance with the present invention;

Figures 3, 4 and 5 are tables of phase-only filter designs and the intensity distributions in the XZ and YZ planes produced using the filters.

As shown in Figures 1a, 1b and 1c a laser focusing system suitable for use in processing of a workpiece consists of a housing 2 that is generally cylindrical within which is positioned imaging optics 3. The housing 2 has opposing windows 4, 5 at each end of the housing, aligned with the imaging optics 3, through which the laser beam passes. The housing 2 also includes a nozzle 6 that is positioned over the work piece when in use and a fluid inlet 7 for the introduction of a pressurised gas into the cavity of the housing. Although not shown, a light source in the form of a laser is aligned with the windows 4, 5 so as to illuminate the workpiece

through the focusing system. The laser may be any one of the many commercially available lasers such as CO_2, excimer or YAG lasers. These lasers are capable of generating light over a broad range of wavelengths from, for example 193 nm with an excimer laser to 10.6 μm with a CO_2 laser.

The imaging optics 3 consists of refractive/reflective lens elements 8,9 (refractive lenses are shown in Figure 1) for producing a single diffraction limited focus and a phase-only filter 10. The phase-only filter 10 may be positioned in the pupil plane of the focusing lens elements as shown in Figure 1a. Alternatively, the filter 10 may be positioned between the lens elements 8, 9 and the workpiece as shown in Figure 1b or between the lens elements 8, 9 and the laser as shown in Figure 1c. The phase-only filter 10 may be fixed in the imaging optics 3 or may be provided in a cartridge that is removably inserted into imaging optics so as to simplify replacement of the filter 10 with alternative phase-only filters, in dependence on the filter most suitable for the particular processing task to be performed.

As shown in Figure 2, laser conditioning apparatus in the form of an adapter 11 may be provided in the form of a cylindrical tube within which is mounted the phase-only filter 10. The adapter 11 includes engaging means for connecting the adapter to the housing of a conventional laser focusing system, between the laser and the window to the housing. In this way, a conventional laser focusing system can be retro-fitted with the phase-only filter so as to enable greater flexibility in the intensity distributions generated by the laser focusing system for use in material processing.

The phase-only filter is preferably square or circular and has a diameter that ideally corresponds to the diameter of the lens elements, for example 38 mm. The filter consists of a plurality of individual regions each assigned a respective phase shift, with the phase shift of each region determined using optimisation software to achieve a predetermined or

target intensity distribution defined in a 3D volume around the original lens focus. Where the filter is a binary filter the individual pixels of the filter cause either a 0 or π radians phase delay. However, more complex filters are also envisaged additionally incorporating phase shifts of 1/2π radians and 3/2π radians, for example. The filter may be a pixellated filter in the form of a programmable spatial light modulator, for example. One preferred filter employs an array of 128 x 128, however, arrays of 1,000 x 1,000 or more are also envisaged. Alternative filters may incorporate ring-shaped, hexagonal or even irregular regions each assigned a predetermined phase shift.

The filter 10 may be fabricated from a fused silica substrate using conventional techniques. For example, a layer of photoresist is applied to the surface of a fused silica substrate. The predetermined design of the filter is then patterned in the photoresist using a chrome mask and conventional contact printing or projection lithographic techniques. The photoresist exposed through the chrome mask is subsequently etched to expose regions of the silica substrate and the exposed silica is then patterned by etching the exposed regions of the silica through the remaining photoresist. The exposed silica is etched to a predetermined depth to achieve the desire phase delay Φ and the remaining photoresist is subsequently removed. The etched depth may be calculated using the following equation:

$$h = \frac{\Phi}{2\pi} \cdot \frac{\lambda}{n - n_0}$$

where h is the etch depth, λ is the wavelength of the incident light, n is the refractive index of the substrate and n_0 is the refractive index of the environment. Thus, for a phase delay of π radians the etch depth is $\lambda/2(n-n_0)$.

The optimisation software, used to determine the design of the filter for any particular target intensity distribution, may employ iterative algorithms such as Direct Binary Search or an iterative inverse Fourier

transform to determine the particular design of the filter. For example, to design a filter for a target intensity distribution $I_T(x,y,z)$ at and around the original lens-only focus, a set of N_T discrete points (x_m,y_m,z_m) are selected in such a way that the intensities at the points $I_{Tm}(x_m,y_m,z_m)$ can serve as a representative set for the continuous distribution $I_T(x,y,z)$.

The lens pupil and the filter are then divided into N_P regions (pixels). By using Fourier optics theory, or by directly evaluating the optical diffraction integrals, the complex amplitudes due to the individual lens regions, the lens pixels, are then calculated at the target points. These lens-only 'pixel contributions' are denoted A_{Lmn}, where $m=1..N_T$ and $n=1..N_P$.

Also, the effect of the phase-only filter is assumed to be a constant Φ_n phase shift within each pixel. The complex amplitude pixel contributions due to the combination of the lens and the filter can then be written as $A_{mn}=A_{Lmn}\exp(i\Phi_n)$.

For any given set of Φ_n pixel phase shift values, the complex amplitudes and intensities at the target points can then be obtained by summation over all the pixels as

$$A_m = \sum_{n=1}^{N_P} A_{Lmn} e^{i\Phi_n} \quad \text{and} \quad I_m = |A_m|^2 . \qquad (1)$$

A g error function is next defined as the metric for the closeness of the desired I_T distribution and the distribution I produced by the lens/filter combination:

$$g = \sum_{m=1}^{N_T} |I_{Tm} - I_m|^2 . \qquad (2)$$

The iterative design algorithm then comprises the following steps:

1) Calculate the A_{Lmn} pixel contributions.
2) Initialise the Φ_n pixel phase shifts to random or predefined values.
3) Calculate the initial error function g_0 using equations (1) and (2).
4) Select a random pixel index.

5) Modify the phase shift value of the selected pixel.
6) Re-calculate the error function.
7) If the new error function value is smaller than the previous one, keep new pixel phase shift value, otherwise reset pixel phase and error function to previous value.
8) Repeat 4) to 7) until changes in *g* become smaller than a predefined limit.

The critical elements of the algorithm are the initial filter phase values, the form of the error function and the way the 'random' pixel indices are generated. The error function can be much more complex than the one shown in (2). For example, it can be highly non-linear, or can even be changed automatically as the algorithm progresses.

In Figures 3, 4 and 5 examples of different filter designs for a 0.1 NA focussing lens and a λ=10.6 µm laser are provided with the black and white representing 0 and π phase shifts. The second column in the Figures is a diagram of the filter design with the third and fourth columns showing the light intensity distributions in the XZ and YZ planes respectively (the Z axis is parallel to the optical axis whereas the X and Y axes are perpendicular to the optical axis) and the fifth column shows on-axis intensity line scans. Figure 3a shows the single focused spot produced by the lens on its own. For the above parameters the single focused spot would be ~0.53 mm long (along the optical axis) and ~53 µm across. Figures 3b-3e show filters designed to produce two on-axis foci with a range of separations between them. Thus, Figure 3b shown two on-axis foci separated by 5 mm whereas the foci produced using the filter of Figure 3e are separated by 20 mm. The filters of Figures 3b to 3e are similar to a Fresnel zone plate, however, they have been optimised to produce only two foci (and not a whole series of diffraction orders) and so the efficiencies of the filters of the present invention are greater than the efficiencies achieved using conventional Fresnel zone plates.

Turning now to Figures 4a to 4d, the phase filters have been designed to produce more than two on-axis foci with Figures 4a, 4b and 4c having equal intensity foci. Figure 4d, on the other hand, shows a four level filter (the grey levels shown in this filter correspond to 0, $1/2\pi$ and $3/2\pi$ phase shifts) that produces three on-axis foci with intensity ratios of 2:3:4. Figures 5a to 5f show the designs of filters for generating more complex intensity distributions. Thus, Figure 5a shows a filter producing a 10 mm long axial line distribution with a 50% intensity spot at each end of the line i.e. ~15 mm apart; Figure 5b shows a filter that produces an intensity distribution similar to that of Figure 5a except that the intensity of the spots is equal to that of the line. In Figure 5c the intensity distribution is similar to that of Figures 5a and 5b except that the intensity of the line is 50% that of the spots. The filter of Figure 5d illustrates that the intensity distribution does not need to have cylindrical symmetry; this filter produces a 10 mm line that is tilted by 2° around the y axis. Figures 5e and 5f illustrate additional filter designs that produce a plurality of intensity peaks in the X-Z plane.

Thus, as has been shown, with the present invention there are few restrictions on the target intensity distributions that can be generated using the laser apparatus of the present invention. With the present invention the phase filter can be designed to meet the desired characteristics of the focal spot of the laser apparatus with respect to: the number of focal spots, spatial positions of the focal spots; the peak intensities; the axial resolution; the radial resolution; and the envelope function. Indeed, arbitrary intensity distributions in all three dimensions can be produced using the present invention. As the intensity distribution of the focal spot(s) can be designed in all three dimensions, high aspect ratio machining of the surface of a workpiece is possible. In particular, an extended on-axis line of equal intensity can be generated that is suitable to machine a channel without the need for the workpiece or the laser apparatus to be moved during the machining to re-focus the laser.

Although reference has been made to the filter being phase-only, it will be apparent that it is not essential for the filter to be phase-only.

Although the present invention has been described above with reference to conventional cutting, welding and machining processes, with the laser apparatus described above micromachining of structures with dimensions as small as 0.25 μm can be achieved. Such micromachining is normally performed using the LIGA process. Using the phase filter of the present invention in combination with conventional lens elements, micromachining with lasers can be achieved with aspect ratios comparable to those achieved with x-rays. Moreover, the laser apparatus is suitable for cutting or otherwise processing a wide range of materials including metals such as steel, wood, plastics including polymers such as PMMA, ceramics and silicon.

CLAIMS

1. Laser apparatus for use in material processing of a workpiece, the apparatus comprising a coherent or partially coherent light source, a housing containing one or more focusing elements and a phase filter, the phase filter having a plurality of regions with each region being assigned a predetermined phase shift from a plurality of possible phase shifts, the phase shifts of the plurality of regions being chosen in dependence on a desired intensity distribution of light incident on the workpiece which extends in at least a spatial dimension parallel to the optical axis beyond the focused spot produced by the apparatus in the absence of the filter.

2. Laser apparatus as claimed in claim 1, wherein the phase filter is mounted in the pupil plane of the one or more focussing elements.

3. Laser apparatus as claimed in either of claim 1, wherein the phase filter is provided in a removable cartridge that is removably mounted within the housing.

4. Laser conditioning apparatus for use in material processing of a workpiece, the conditioning apparatus comprising an adapter housing containing a phase filter, the adapter housing having connection means for mounting the adapter housing between a coherent light source and one or more focusing elements, the phase filter having a plurality of regions with each region being assigned a predetermined phase shift from a plurality of possible phase shifts, the phase shifts of the plurality of regions being chosen in dependence on the desired intensity distribution of light incident on the workpiece which extends in at least one spatial dimension beyond the focused spot produced by laser apparatus in the absence of the filter.

5. Apparatus as claimed in any one of the preceding claims, wherein the phase filter is a programmable spatial light modulator.

6. Apparatus as claimed in any one of the preceding claims, wherein each region of the filter has a phase shift of either 0 or π radians.

7. Apparatus as claimed in any one of the preceding claims, wherein the phase filter produces a desired three dimensional geometry of the light incident on the workpiece.

8. Apparatus as claimed in any one of the preceding claims, wherein the phase filter produces a plurality of separate intensity peaks.

9. A method of manufacturing a phase filter for use in laser material processing apparatus, the method comprising the steps of: determining a desired intensity distribution of light incident on a workpiece which extends in at least a spatial dimension parallel to the optical axis beyond the focused spot produced by the laser material processing apparatus in the absence of the filter; assigning initial respective phase shifts to a plurality of regions of the filter; determining an error factor with respect to the similarity of the intensity distribution generated using the assigned phase shifts to the desired intensity distribution; iteratively optimising the phase shifts assigned to each region so as to determine final phase shifts for each region of the filter; and generating a phase filter with a plurality of regions, each region having the final phase shift determined by the iterative optimisation step.

10. A method as claimed in claim 9, wherein the assigned phase shifts are iteratively optimised using a direct binary search.

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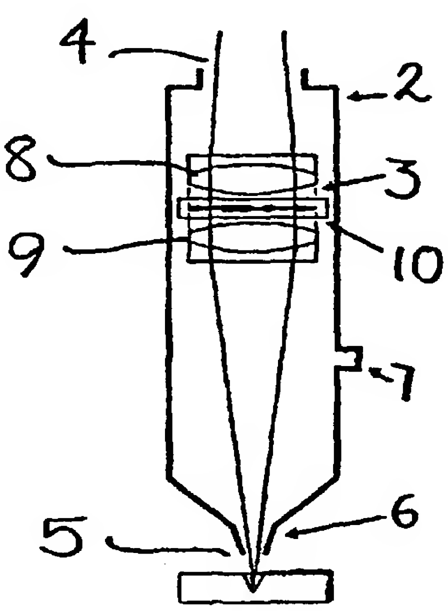
(54) Title: LASER APPARATUS FOR USE IN MATERIAL PROCESSING



(57) Abstract: The laser has a focusing system including a housing (2) with opposing transparent windows (4, 5) between which imaging optics (3) are positioned. The housing (2) also has an inlet (7) for the introduction of pressurised gas into the cavity of the housing. The imaging optics (3) include refractive/reflective lens elements (8, 9) and a phase-only filter (10). The filter (10) has different regions each assigned a particular phase-shift and may be implemented in the pixels of a spatial light modulator or using a fused silica structure that has regions etched to differing depths to achieve differing phase delays by means of the remaining thickness of the silica at each of the regions. The filter (10) ensures that the laser beam incident on a workpiece that is to be cut, for example, has an intensity distribution which extends beyond the focussed spot in at least one dimension. With this laser high precision as well as high speed cutting or welding can be performed using an optimised light distribution.

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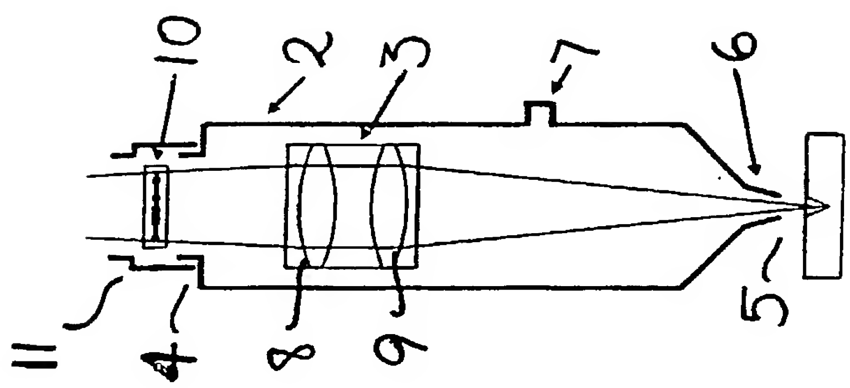


Figure 2

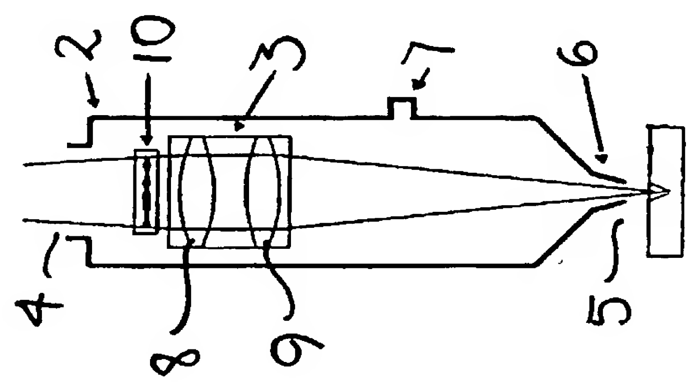


Figure 1c

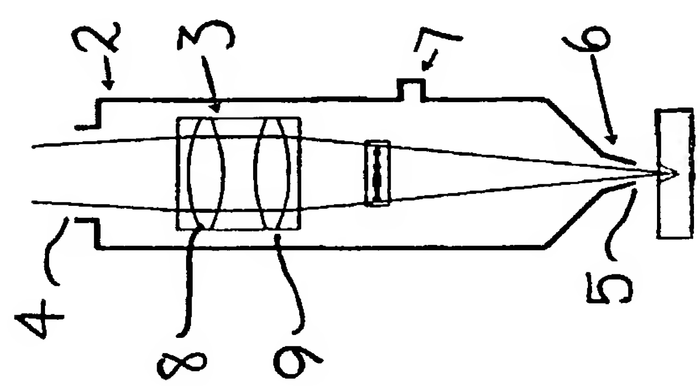


Figure 1b

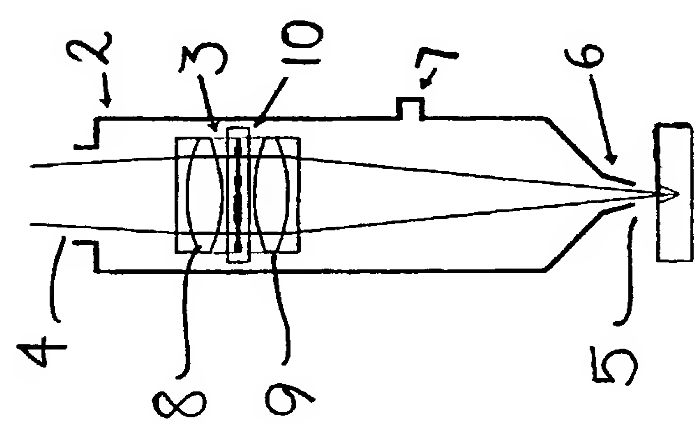


Figure 1a

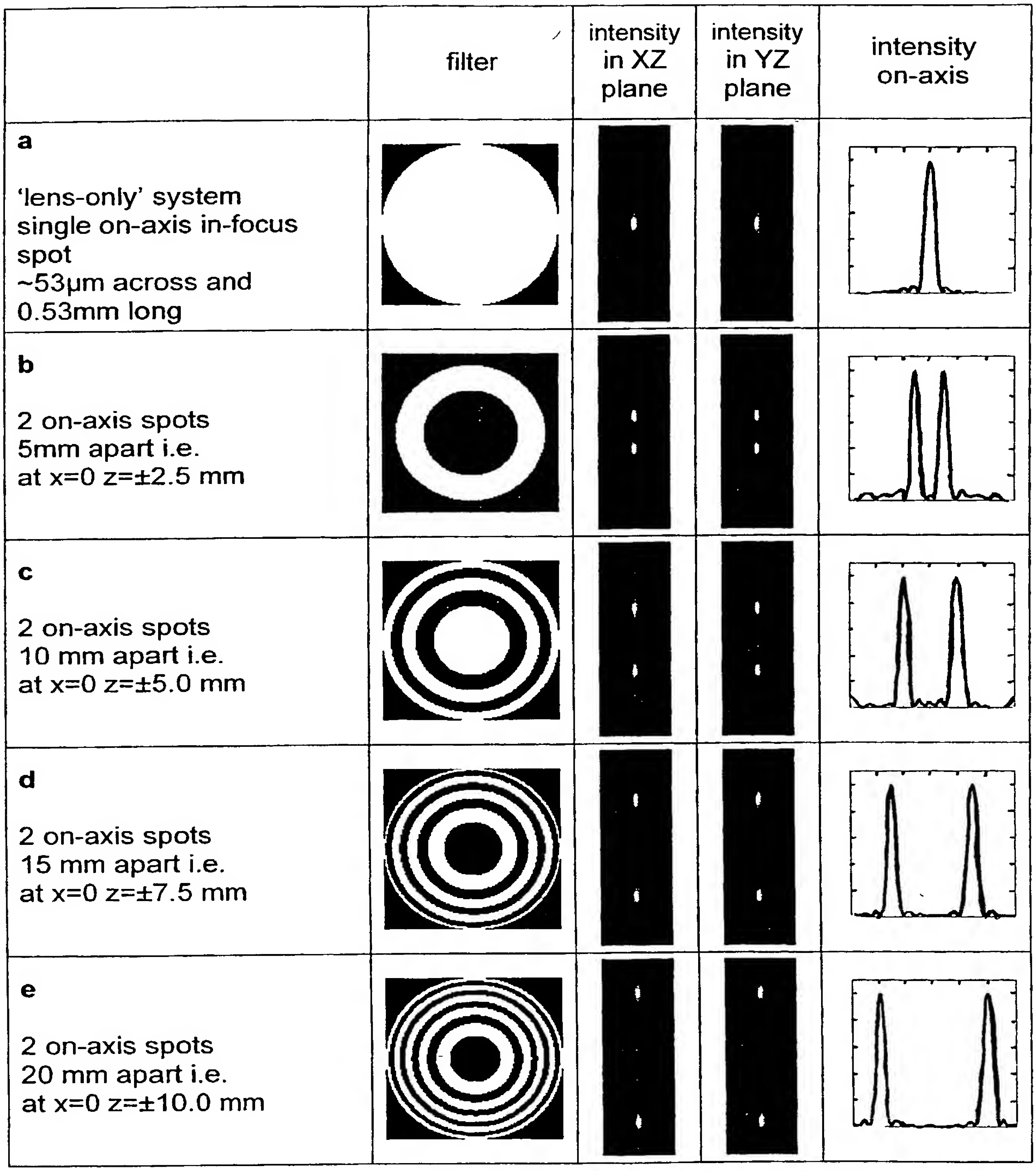

filter
intensity in XZ plane
intensity in YZ plane
intensity on-axis
a
'lens-only' system single on-axis in-focus spot ~53μm across and 0.53mm long
b
2 on-axis spots 5mm apart i.e. at x=0 z=±2.5 mm
c
2 on-axis spots 10 mm apart i.e. at x=0 z=±5.0 mm
d
2 on-axis spots 15 mm apart i.e. at x=0 z=±7.5 mm
e
2 on-axis spots 20 mm apart i.e. at x=0 z=±10.0 mm

Figure 3

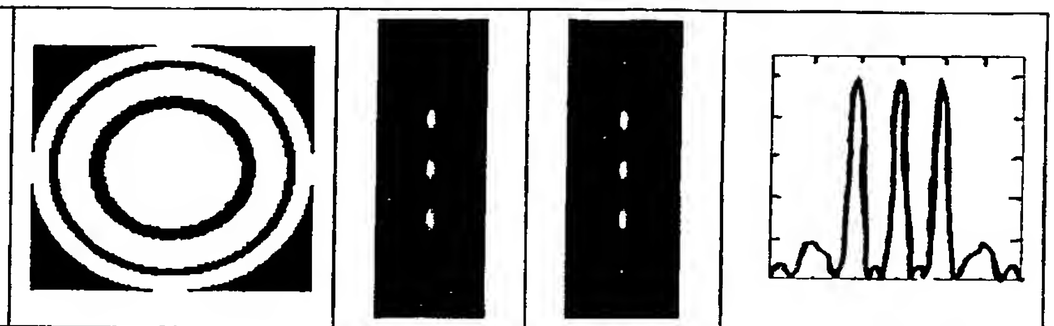
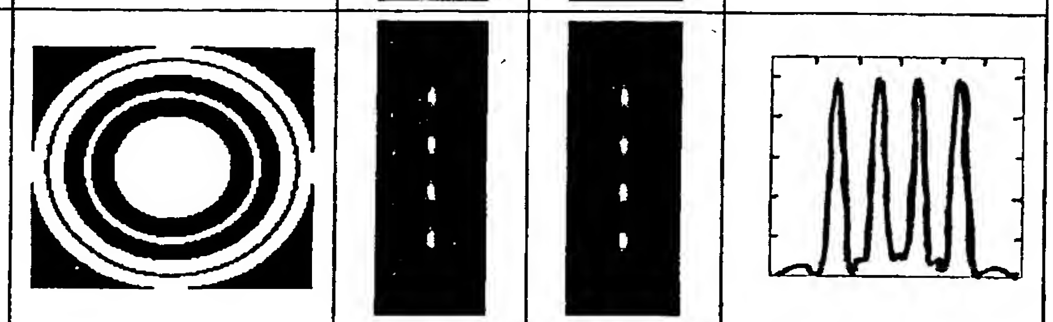
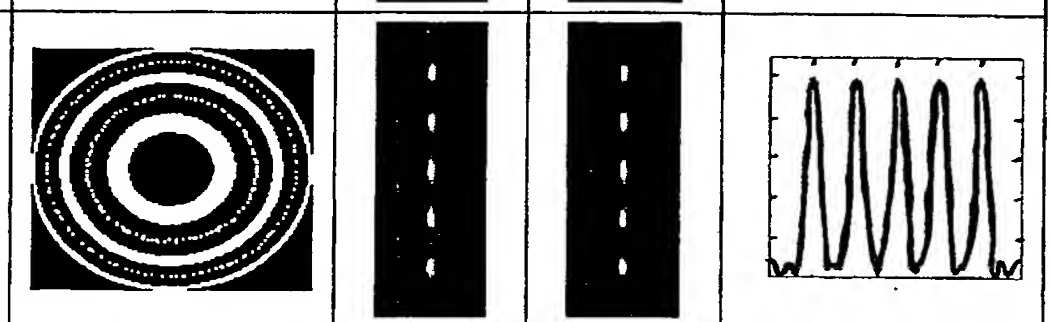
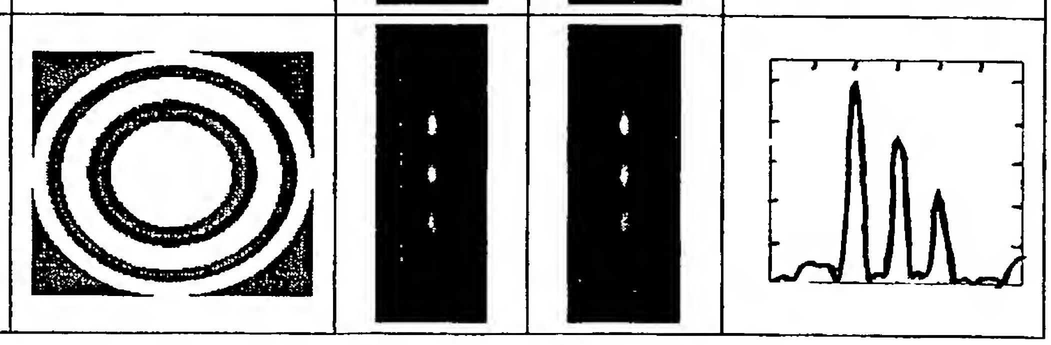
a 3 on-axis spots 5 mm apart i.e. at x=0 z=0 and ±5.0 mm	
b 4 on-axis spots 5 mm apart i.e. at x=0 z=±2.5 and ±7.5 mm	
c 5 on-axis spots 5 mm apart i.e. at x=0 z=0, ±5.0 and ±10.0 mm	
d 3 on-axis spots 5 mm apart i.e. at x=0 z=0 and ±5.0 mm with intensity ratios of 2:3:4	

Figure 4

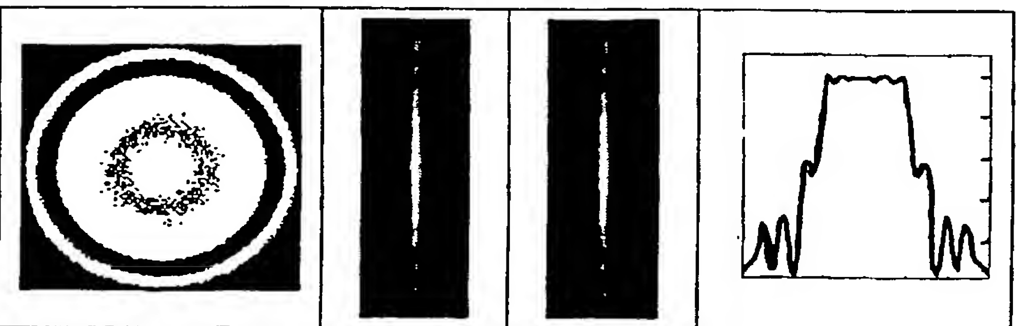
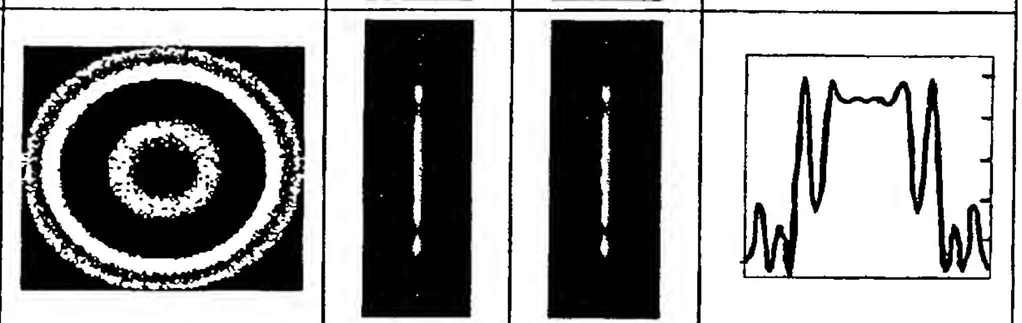
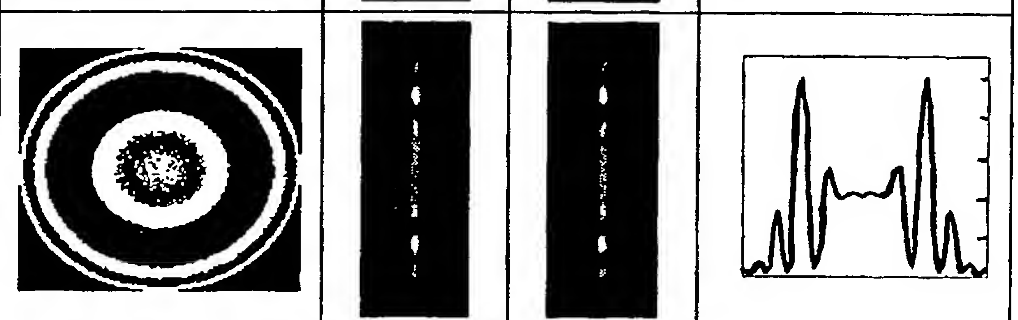
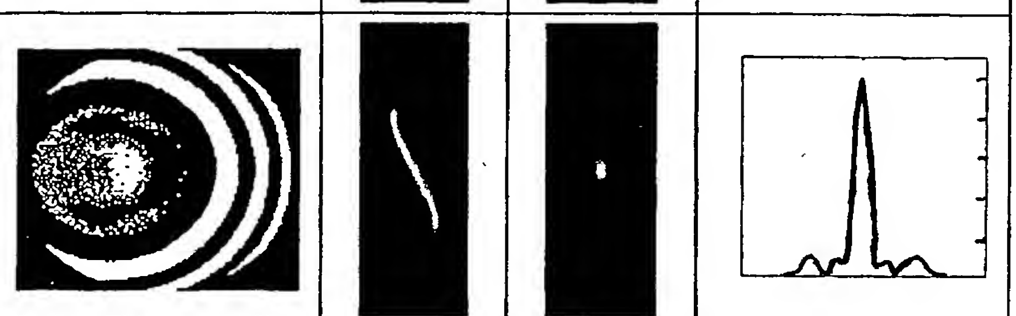
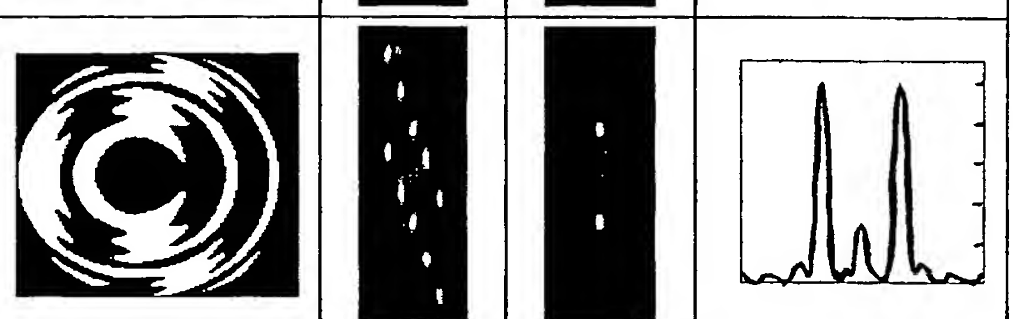
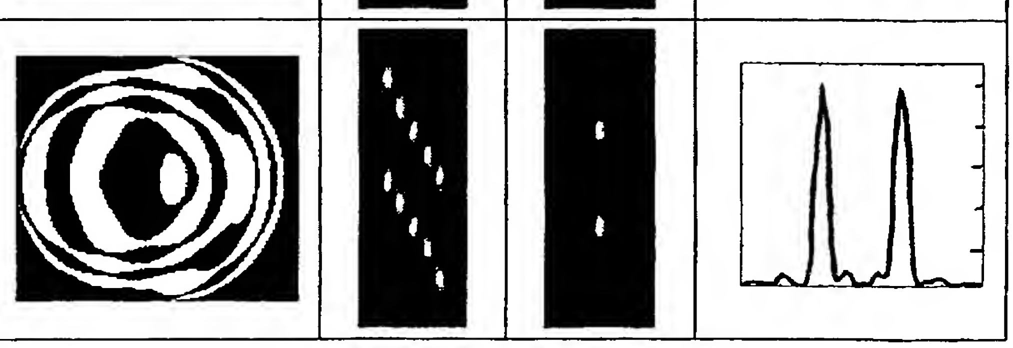
a 10 mm long axial line and two 50% intensity spots 15 mm apart i.e. at x=0 z=±7.5 mm	
b 10 mm long axial line and two spots 15 mm apart i.e. at x=0 z=±7.5 mm	
c two axial spots 15 mm apart i.e. at x=0 z=±7.5 mm and a 50% intensity 10 mm long line between them	
d 10 mm long line tilted by 2° around the Y axis i.e. with end points at x=-0.175 z=5 mm and x=0.175 z=-5 mm	
e 5 pairs of spots at x=-0.2, -0.1, 0, 0.1 and 0.2mm $z=z_0\pm5$mm with z_0=0, ±3.5 and ±7mm	
f 5 pairs of spots at x=-0.2, -0.1, 0, 0.1 and 0.2mm $z=z_0\pm5$mm with z_0=0, ±2.5 and ±5mm	

Figure 5

PATENT
Attorney Docket No. 9267-17

DECLARATION AND POWER OF ATTORNEY

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are stated below next to my name:

I believe I am the original, first, and sole inventor (if only one name is listed below) or an original, first, and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled:

LASER APPARATUS FOR USE IN MATERIAL PROCESSING

---

the specification of which is attached hereto unless the following box is checked

☒ was filed on September 12, 2000 as Application No. ________________ or PCT Application No. PCT/GB00/03496 and amended on December 17, 2001 and March 18, 2002 (if applicable).

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information which is material to the patentability of this application in accordance with 37 CFR §1.56.

I hereby claim foreign priority benefits under 35 U.S.C. §119(a)-(d) or §365(b) of any foreign application(s) for patent or inventor's certificate, or §365(a) of any PCT international application which designated at least one country other than the United States, listed below and have also identified below any foreign application for patent or inventor's certificate or PCT International application having a filing date before that of the application on which priority is claimed:

PRIOR FOREIGN/PCT APPLICATION(S)

COUNTRY/OFFICE	APPLICATION NO.	DATE OF FILING	PRIORITY CLAIMED	
GB	9922082.4	September 17, 1999	☒YES	NO ☐
			☐YES	NO ☐
			☐YES	NO ☐

I hereby claim the benefit under 35 U.S.C. §119(e) of any United States provisional application(s) listed below.

PROVISIONAL APPLICATION NUMBER	**DATE OF FILING**

I hereby claim the benefit under 35 U.S.C. §120 of any United States application(s) or §365(c) of any PCT International application(s) designating the United States, listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States application in the manner provided by the first paragraph of 35 U.S.C. §112, I acknowledge the duty to disclose material information as defined in 37 CFR §1.56 which became available between the filing date of the prior application and the national or PCT international filing date of this application:

PRIOR U.S. APPLICATIONS OR PCT INTERNATIONAL APPLICATIONS DESIGNATING THE U.S. FOR BENEFIT UNDER 25 U.S.C. §120

Application Serial No.	**Date of Filing**	**Status (check one)** Patented	Pending	Abandoned
8		☐	☐	☐

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I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application or any patent issuing thereon.

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